

## Modeling the Galactic Magnetic Field using Rotation Measure Observations in the Galactic Disk from the CGPS, SGPS, and the VLA

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### Abstract.

Interstellar magnetic fields play critical roles in many astrophysical processes. Yet despite their importance, our knowledge about magnetic fields in our Galaxy remains limited. For the field within the Milky Way, much of what we do know comes from observations of polarisation and Faraday rotation measures (RMs) of extragalactic sources and pulsars. A high angular density of RM measurements in several critical areas of the Galaxy is needed to clarify the Galactic magnetic field structure. Using observations made with the VLA, we have determined RMs for sources in regions of the Galactic plane not covered by the Canadian Galactic Plane Survey (CGPS) and Southern Galactic Plane Survey (SGPS). We have combined these new RMs with those determined from the CGPS and SGPS and have produced a new model for the magnetic field of the Galactic disk.

### 1. Introduction

The Galactic magnetic field plays critical roles in the interstellar medium, ranging from star formation to large-scale galactic dynamics. However, much remains unknown about how the field is generated or how it is evolving. The only way to make progress in addressing these questions is to fully understand the present overall structure of the field. This is an essential constraint to proposed evolutionary models of the field.

One observation essential to the study of the Galactic magnetism is that of the rotation measure (RM). As a linearly polarised electromagnetic wave propagates through a region containing free thermal electrons and a magnetic field, such as the interstellar medium, the plane of polarisation will rotate through the process known as Faraday rotation. If we assume the polarised radiation emitted by a source is at a constant angle,  $\tau_o$ , and that this radiation is *only* affected by Faraday rotation, then the polarisation angle that we measure,  $\tau$ , will be given by

$$\tau = \tau_o + 0.812\lambda^2 \int_{\text{source}}^{\text{receiver}} n_e \mathbf{B} \cdot d\mathbf{l} = \tau_o + \lambda^2 \text{RM}, \quad (1)$$

where  $\lambda$  is the wavelength,  $n_e[\text{cm}^{-3}]$  is the electron density,  $\mathbf{B}[\mu\text{G}]$  is the magnetic field,  $d\mathbf{l}[\text{pc}]$  is the path length element. Consequently, measuring the polarisation angle at several wavelengths for a given source can provide a simple determination of the rotation measure for that line of sight. Compact polarised radio sources within the Galaxy (pulsars) and outside the Galaxy (extragalactic sources or EGS) subsequently

act as line-of-sight probes for the magnetic field; the higher the projected spatial density of the observed probes, the easier it is to determine the field structure in the given region.

Recent work has focused on developing and testing competing models and on determining the existence of large scale reversals in the magnetic field. Magnetic field reversals occur where the magnetic field direction completely reverses over a short change in radius and/or azimuth within the disk of the Galaxy. The number of reversals depends on the interpretation of the existing RM data and is presently a very controversial subject (e.g. Brown & Taylor 2001; Weisberg et al. 2004; Han et al. 2006; Brown et al. 2007; Sun et al. 2008; Vallée 2008; Men et al. 2008; Jansson et al. 2009; Nota & Katgert 2010). Most models are made to follow the spiral arm structure of the Galaxy since an approximate alignment of the regular magnetic fields and spiral arms is commonly observed in external galaxies (e.g. Patrikeev et al. 2006). For all of these models, sufficient numbers of low-latitude, high quality RM data in key regions have been lacking.

## 2. Observations

Two recent projects have produced catalogues for several hundred EGS RMs in the plane of the Galaxy: the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003; Brown et al. 2003a) and the Southern Galactic Plane Survey (SGPS; Haverkorn et al. 2006; Brown et al. 2007). These surveys left two gaps in the EGS RM coverage of the Galactic plane as shown in Figure 1. Using the Very Large Array (VLA), we performed observations to fill in the gaps in RMs for EGS between the CGPS and SGPS.

From the VLA observations, we determined reliable RMs for 221 EGS, 96 of which are in quadrant 1 and 125 in quadrant 3. For details on the processing and the RM catalog, see Van Eck et al. (2010). These RMs are shown in Figure 2, in comparison with the previously published RMs in these regions.

## 3. Multi-sector Model of the Magnetic Field in the Galactic Disk

Many recent works have focused on building an empirical model of the magnetic field for the whole Galaxy (e.g. Weisberg et al. 2004; Han et al. 2006; Vallée 2008). By contrast, we have chosen to take a ‘hybrid’ approach to our modeling work. We examine the entire Galactic disk, but in 3 separate sectors to see if we can determine any common features or structure across the sectors. We purposely do not apply any ‘boundary matching’ conditions between the sectors in order to facilitate independent results for each of the three sectors examined. It was our intention to see if there was any commonality amongst the different sectors that could be arrived at independently. The three sectors we examine are as follows: the outer Galaxy, defined roughly as spanning quadrants 2 and 3 (Q2 and Q3), and the two inner Galaxy regions, roughly defined by quadrants 1 and 4 (Q1 and Q4).

We use the method described by Brown et al. (2007) and in greater detail in Brown (2002). In summary, we attempt to empirically reproduce the observed RMs of both pulsars and EGS using the electron density of Cordes & Lazio (2002, hereafter NE2001), and various magnetic field models. With the goal of our modeling being to explore the large-scale field, we ignore the small-scale clumps and voids of NE2001, and use only the thin, thick, and spiral arm components.

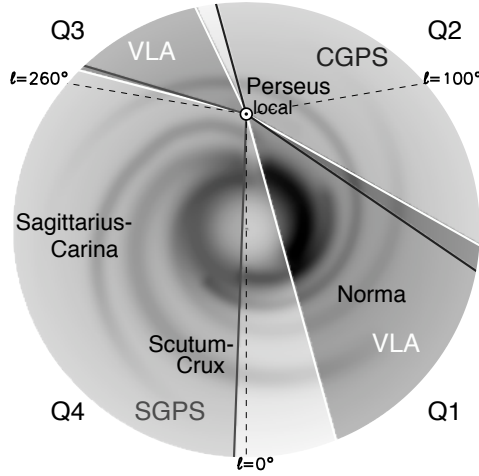


Figure 1. View of the Milky Way from above the north Galactic pole illustrating the main survey regions of extragalactic rotation measures used in this paper. The grey scale background is the electron density distribution model of Cordes and Lazio (2002). The dark lines are the boundaries of the regions observed by the CGPS and SGPS, while the white lines denote the 2 areas targeted by the VLA data used for this project. The dashed lines show the delineations between the three sections we modeled.

We also placed the following restrictions on all of the models we investigated. First, the magnetic field for Galactocentric radii  $R > 20$  kpc or  $R < 3$  kpc was set to zero. Similarly, the field was assumed to be zero for  $|z| > 1.5$  kpc. In addition, all models have a circular region containing the molecular ring of the NE2001 electron model ( $3 \text{ kpc} \leq R \leq 5 \text{ kpc}$ ) with a circular magnetic field regardless of the geometry being tested in the rest of the Galaxy.

We used EGS RMs our VLA observations discussed here, as well as the SGPS and CGPS data sets. We treated the EGSs as being located at the edge of the Galaxy (modeled as  $R = 20$  kpc). Since we did not wish to investigate the complicated nature of the field likely to be found near the Galactic center, we did not use any EGS RM sources within  $\pm 10^\circ$  Galactic center. Since we did not consider any vertical structure in our model, we removed any sources with a calculated height  $|z| > 1.5$  kpc. With these criteria, we were left with 211 of the 221 RMs described in section 2, 142 of the 148 RMs from the SGPS and 1020 sources from the CGPS, a total of 1373 EGS sources.

We used 557 pulsar RMs from the following sources: Noutsos et al. (2008), Han et al. (2006), Weisberg et al. (2004), Mitra et al. (2003), Han et al. (1999) and Taylor et al. (1993) where pulsars were selected with  $|z| < 1.5$  kpc. For self-consistency, we used distances to the pulsars predicted by the NE2001 model.

The EGS and pulsar RMs were then split into the sectors described in the next section. Using the resulting best-fit values for the magnetic field model, we could then calculate ‘predicted’ RMs and compare them to the observed RMs. Through this comparison, we could assess the quality of fit and vary the model in each sector to test for different attributes of the magnetic field. Below we present what we found to be our best model in each sector. Additional details of our modeling and the assessment of the quality of fit is given in Van Eck et al. (2010).

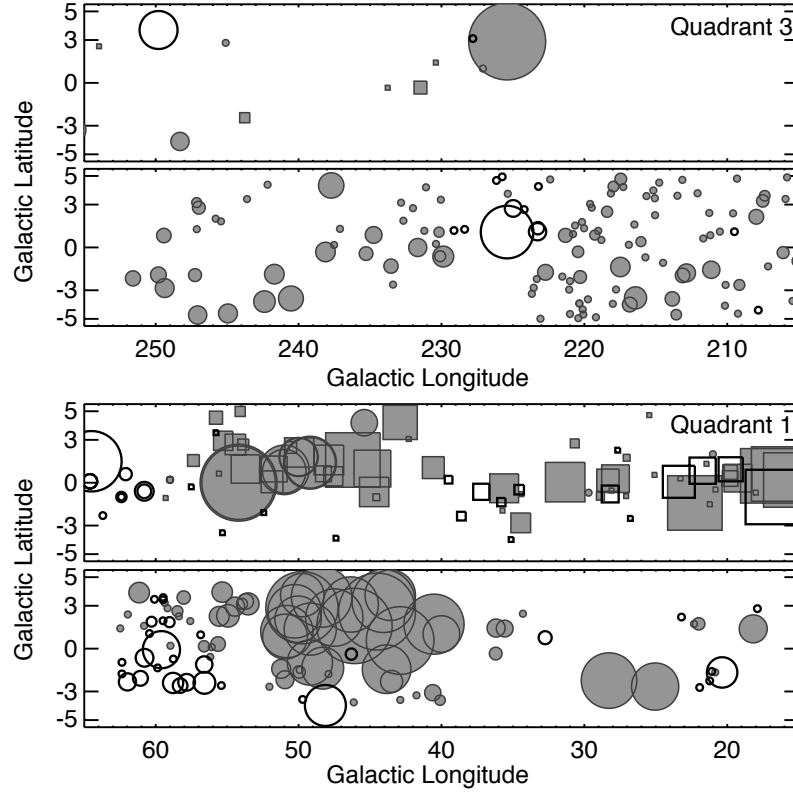


Figure 2. A comparison of RMs in the VLA regions before and after the Van Eck et al. (2010) catalog. The top panels for each quadrant (1 and 3) are previous EGS (circles) and pulsar (squares) RMs. The bottom panels for each quadrant are the new EGS RMs (circles). Grey filled symbols represent positive rotation measures; black open symbols represent negative rotation measures; diameters of symbols are linearly scaled to the magnitude of RM truncated between 100 and 600  $\text{rad m}^{-2}$  so that sources with  $|\text{RM}| < 100 \text{ rad m}^{-2}$  are set to 100  $\text{rad m}^{-2}$ , and those with  $|\text{RM}| > 600 \text{ rad m}^{-2}$  are set to 600  $\text{rad m}^{-2}$ .

### 3.1. Model Sector I: The Outer Galaxy (Q2 and Q3)

This sector is strictly the outer Galaxy, which we define to be  $100^\circ < \ell < 260^\circ$ . Based on previous experience, we expected this region to be the simplest in nature. Within this region, we have RMs for 88 pulsars, and 864 EGS (21 from SGPS, 125 VLA, 718 from CGPS).

As demonstrated by earlier CGPS work, RM data in the outer Galaxy hold no strong evidence for a reversal (Brown & Taylor 2001; Brown 2002; Brown et al. 2003b). There is some evidence that suggests that the field decays as  $1/R$ , consistent with the decay in electron density (Brown et al. 2003b). Therefore, we modeled this region as a single magnetic entity with a  $1/R$  decay in magnitude. Coupled with the results of Rae et al. (these proceedings), we found a purely azimuthal field to fit the best in this region.

### 3.2. Model Sector II: SGPS region (Q4)

We define this region to be  $260^\circ < \ell < 360^\circ$ , which is slightly less than the area modeled by Brown et al. (2007). This region contains 292 pulsars and 121 EGS (all from the SGPS).

For their model, Brown et al. (2007) used the available pulsar RMs combined with new EGS RMs from the SGPS to model the magnetic field within the SGPS region. Given how well the model agreed with the data, we decided to keep much of this model the same, but revise it slightly to agree with the findings of our model sector I. To that end, we merged all separate regions beyond the Sagittarius-Carina arm into one magnetic field region, and redefined the field in this new outer-Galaxy region to be purely azimuthal, and retained the  $1/R$  dependence in this region, consistent with Brown et al. (2003b) and Brown et al. (2007). However, for the remaining regions in the inner Galaxy we reverted to a constant field strength as suggested by Nota & Katgert (2010).

The best-fit magnetic field results for our variation on the Brown et al. (2007) model produced predicted RMs that are virtually indistinguishable from that of the original model. However, this new model is less complicated as it has 8 regions compared to 9 regions in the original model, and has removed the complexity of the  $1/R$  dependence in the inner Galaxy. The reduction in the number of parameters while maintaining a good quality of fit, lends support to this model.

### 3.3. Model Sector III: VLA region (Q1)

We define this region to be  $0^\circ < \ell < 100^\circ$ . In this region, we have 177 pulsar RMs and 388 EGS RMs (302 from CGPS, 86 from our VLA observations).

For this sector, we used as our starting position the ASS+RING model proposed by Sun et al. (2008). In particular, we began by assuming that in the inner Galaxy, the magnetic region delineations are circular, but the fields within the regions are spiral. We again carried over the circular,  $1/R$  outer Galaxy field from sector I.

For our model, the first region boundary is located at  $R = 5.0$  kpc to correspond to the molecular ring, and to be consistent with the Q4 model. The remaining boundary locations were optimized based on a comparison between the predicted RMs and the modeled RMs; they were found to be  $R = 5.7$  kpc,  $R = 7.2$  kpc, and  $R = 8.4$  kpc.

For this region, our best fit magnetic field model has the inner Galaxy primarily oriented counter-clockwise, except for one small clockwise piece next to the molecular ring, as shown in Figure 3.

### 3.4. Combining the Sectors

When we consider our three sectors together, as shown in Figure 3, a picture emerges of a predominantly clockwise Galactic magnetic field with what could be interpreted as single reversed (counter-clockwise) region spiraling out from the Galactic center. According to our analysis, the field in the inner Galaxy has a spiral shape (with a pitch angle estimated here as  $11.5^\circ$ ) and is generally aligned with the spiral arms while in the outer Galaxy it is (almost) azimuthal. Our model may be considered as something of a zeroth-order approximation; it was constructed in a piece-wise manner, yet there is some consistency across the whole of the Galaxy. We also note that this ‘spiraling-out’ reversed region could extend into Q1 at larger Galactic radii, but without any pulsars located on the far side of the Galaxy in this region, determining the existence of such a region is not possible.

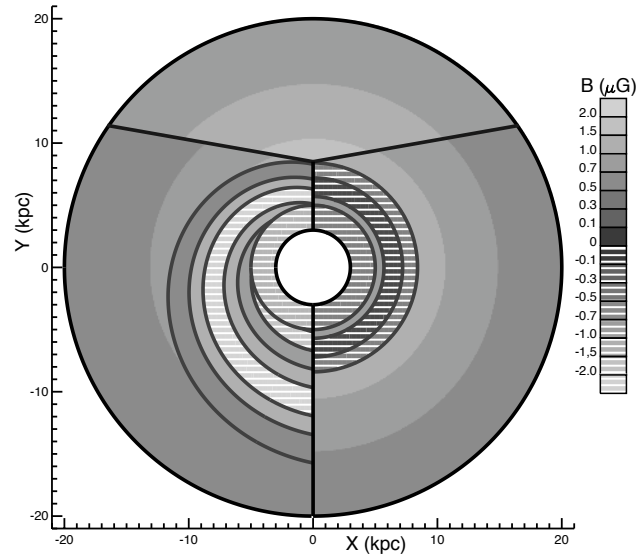


Figure 3. Best-fit magnetic field strengths for each of the regions. Solid shades represent clockwise field, while striped shades represent a counter-clockwise field.

We expect that significant improvements on this model, using the same technique and the present edition of the electron density model, will be difficult to accomplish for several reasons. First, the electron density includes very little small scale structure beyond the local regions. Second, the reliability of distances to the pulsars remains questionable; small shifts in the assumed position of the pulsars will influence the results of the best fit. Finally, as is always the case with modeling, more data would vastly improve the model. For example, pulsars on the far side of the Galactic center would provide much needed constraints in the area, and as discussed above, the EGS source density is considerably lower in this part of the inner Galaxy as well. However, such data are unlikely to be available until higher sensitivity instruments, such as ASKAP or the SKA come online.

#### 4. Summary and Discussion

We have produced a catalog of 221 rotation measures of extragalactic sources to fill in critical gaps in the disk rotation measure coverage of the Canadian Galactic Plane Survey and the Southern Galactic Plane Survey. We then used these data, in conjunction with previously observed rotation measures, to propose a new magnetic field model, stemming from a new modeling strategy that studies the disk field in three different sectors. The division of sectors is roughly between the outer Galaxy (quadrants 2 and 3), and the two ‘inner Galaxy’ quadrants: quadrant 1 and quadrant 4. Our modeling suggests that the outer Galaxy is dominated by an (almost) purely azimuthal field, whereas in the inner Galaxy magnetic lines have a spiral shape, and are likely to be aligned with the spiral arms. Furthermore, the model seems to indicate that the magnetic field in the Galaxy is predominantly clockwise, with a single reversed region that appears to spiral out from the center of the Galaxy.

Additional observations, and more modeling work are needed to confirm our results. However, we believe that this multi-sector approach to empirical modeling yields a more reasonable model than attempting to model the entire Galaxy with the current status of both the electron density and available data.

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